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Some current findings on brain characteristics of the mathematically gifted adolescent

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A number of studies investigating the brain characteristics of mathematically gifted youth indicate that they possess a unique functional organisation as compared to those of average math ability (O'Boyle, et al., 1995). Specifically, data from a variety of behavioural and psychophysiological experiments tend to suggest enhanced processing reliance on the right cerebral hemisphere and heightened interhemispheric communication, as unique functional characteristics of the math gifted brain, with the later providing supplemental processing resources and enhanced cooperation between the cerebral hemispheres. Notably, these brain differences may have important implications for the nature and timing of mathematics instruction.

Brain characteristics, mathematically gifted adolescent

INTRODUCTION

A selective review of published findings (for example, Butterworth, 1999; Dehaene, 1997) may be interpreted as supporting two potential neurobiological mechanisms underlying exceptional mathematical ability. One mechanism postulates an enhanced role for the right cerebral hemisphere (RH), while the other entails greater bilateral involvement of the cerebral hemispheres, with the later being related to heightened interhemispheric connectivity (O'Boyle and Hellige, 1989; O'Boyle, et al., 1995). Evidence from brain-damaged patients indicates that deficits in mathematics can follow injury to either cerebral hemisphere, but that the nature of the impairment will differ depending upon the locus of the cerebral insult. For example, left hemisphere (LH) damage may result in difficulties with reading or writing numbers and the performance of basic arithmetic operations (for example, acalculia or dyscalculia) while damage to the RH disrupts spatial representation (for example, misreading signs, omitting numbers, difficulties in preserving decimal places), and often impairs higher-order mathematical reasoning capacity (Benbow, 1988; Dehaene and Cohen, 1997). In this way both hemispheres of the brain and their successful interaction play a crucial role in the complex process of mathematics (Dehaene, et al., 1998).

Data derived from several psychophysiological studies support an important relationship between the specialised capacities of the RH and mathematical ability. For example, using positron emission tomography (PET), Haier and Benbow (1995) showed increased glucose metabolism in the right temporal lobe during a mathematical reasoning test of high (but not gifted) ability students. And recently, Presenti, et al. (2001) also using PET measures, found calculation in an adult mathematical prodigy to be uniquely mediated by right prefrontal and right medial temporal cortex. In still other studies, the interactive contributions of both hemispheres to the various components of mathematical reasoning have been demonstrated using the Electroencephalogram (EEG) and Event Related Potential (ERP) techniques, with the relative importance of each hemisphere being task and strategy dependent (for example, Burbaud et al., 1999; Kazui, et al., 2000). Interestingly, a recent post-mortem examination of the brain of Albert Einstein (Witelson, et al., 1999) found enhanced development of the parietal lobes, particularly on the right side, which is the very area implicated in our ongoing studies of math gifted adolescents.

Over the last decade, O'Boyle and colleagues have conducted a considerable amount of research focusing on the morphological and functional characteristics of the mathematically gifted brain, and how it differs both qualitatively and quantitatively, from those of average math ability (O'Boyle and Benbow, 1990; O'Boyle and Gill, 1998; O'Boyle, 2000; O'Boyle, et al., 1991, 1994, 1995). In these studies a variety of experimental methods have demonstrated that enhanced development of the RH and an unusual reliance upon it when processing information are unique characteristics of the math gifted brain. Note that math gifted individuals are operationally defined as 10-15 year olds who have scored at the 99th percentile when taking the SAT-Math exam (Scholastic Aptitude Test, USA) or the SCAT-Numerical Reasoning test (School College Abilities Test, Melbourne, Australia), which places them over two standard deviations beyond the mean.

Using a dichotic listening paradigm O'Boyle and Benbow (1990) have demonstrated that adolescents of average math ability show the prototypic right ear/LH advantage when recognising linguistic stimuli like syllables (Kimura, 1967), while contrastingly, the mathematically gifted are equally able at recognising these verbal stimuli with either ear. The later finding suggests the enhanced involvement of the RH during information processing, even for the analysis of materials that are usually LH mediated. Likewise, O'Boyle et al. (1994) had mathematically gifted and average ability youths perform a concurrent finger-tapping task, one that involves tapping a key with the index finger of each hand (one hand at a time) while simultaneously reading a paragraph out loud. Average ability participants showed a significant reduction in tapping rate for the right hand/LH, with their left-hand rate tapping virtually unaffected. This pattern is thought to reflect a division of LH (but not RH) resources between the linguistic processes necessary for reading and those required for motor control of the right finger. For the math gifted, however, significant reductions in the tapping rate of both hands were observed. The pattern found in the math gifted dovetails with the aforementioned dichotic listening results, and supports the idea of enhanced development of the RH and reliance upon a special form of bilateralism when processing information, even when engaged in the analysis of linguistic (predominantly LH) inputs.

There is also evidence of a highly coordinated and orchestrated ability to switch activation (and presumably information) between the hemispheres in the brain of the math gifted (O'Boyle, et. al., 1995; O'Boyle, 2000; O'Boyle and Gill, 1998; Singh and O'Boyle, 2004). This is thought to reflect enhanced interhemispheric connectivity, perhaps via the corpus callosum (CC) which is the major anatomical conduit between the left and right hemispheres. For example, Singh and O'Boyle (2004) found average math ability children to be faster and more accurate at making same/different judgments of letter pairs when they were presented unilaterally (that is, both letters of the pair presented to the same hemisphere) as compared to bilaterally (that is, when one letter of the pair is presented to each hemisphere simultaneously, thus requiring interhemispheric exchange of information to perform the task). In contrast, the mathematically gifted were faster and equally accurate on bilateral trials as compared to unilateral trials, suggestive of a brain organisation that is uniquely predisposed towards a high degree of interhemispheric interaction, and as such is characterised by rapid and accurate information exchange between the cerebral hemispheres.

Thus, the available empirical evidence pinpoints enhanced RH mediation and heightened bilateral involvement of the cerebral hemispheres as two possible neurobiological mechanisms that underlie exceptional mathematical ability. The functional organisation of the math gifted brain, however, has only recently begun to be investigated, and new research using advanced brain imaging techniques is required for a better understanding of the neurobiological substrate of children who display gifted mathematical ability.

METHODS AND RESULTS

To further investigate possible differences in the functional brain organisation of mathematically gifted adolescents compared to those of average math ability, we recently used functional magnetic imaging (fMRI) to monitor brain activation during performance of a mental rotation task. Success at mental rotation, although visuospatial in nature, is often reported to correlate with mathematical ability (that is, the better mental rotation, the higher the math ability, see Benbow, 1988). In the present study we had eight mathematically gifted boys (mean age =14 years) perform mental rotation problems while inside the fMRI scanning environment. On each trial participants were required to press one of four fibre optic buttons to indicate which of the four test objects was identical to the target object when rotated in space, as presented in the example trial in Figure 1.

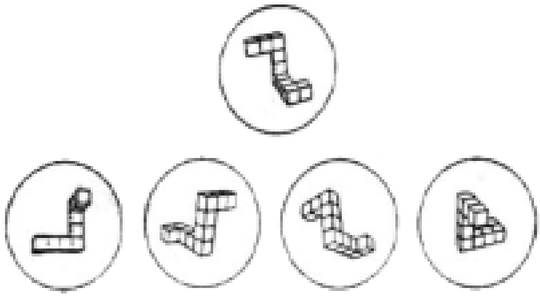

Figure 1. Mental rotation example

As can be seen in the accompanying head plot, shown in Figure 2, significant brain activation ($p_{corr}<0.05$) was obtained bilaterally in the parietal, superior occipital, and pre-motor areas, and in the right lateral frontal cortex (Brodmann 44), with somewhat less activation in right lateral frontal, right anterior cingulate and right caudate regions. A trend towards activation of the left anterior cingulate, and bilaterally in the anterior insula was also noted, but lacked statistical power given the small number of participants. In the parietal and the occipital areas the volume of activation was somewhat greater in the RH as compared to the LH. These results, although preliminary in nature, suggest that math gifted male adolescents recruit areas in both cerebral hemispheres when performing mental rotation (particularly, the right parietal), and engage other regions not typically found in previous rotation studies of young adults, namely bilateral activation of prefrontal cortex and the anterior cingulate. The later regions are known to mediate enhanced spatial attention and working memory, as well as the fine-tuning of executive functions (for a review see Kane and Engle, 2002). And, they are also thought to play an important role in the development of deductive reasoning and cognitive expertise (Knauff, et al., 2002).

DISCUSSION

There is now, and has always been, intense fascination with individuals who exhibit exceptional mathematical ability, particularly adolescents who acquire prodigious math skills in the absence of any formal training or instruction. Everyone seems to know someone who has an innate proclivity for mathematics and each of us shares an intrinsic curiosity about how the brain of a ‘budding Einstein’ might work relative to the rest of us. Of particular importance is the capacity to identify children who are gifted in mathematics, and how to foster and develop their inherent ability to its full potential. While the present findings are provocative, our current understanding of the biological bases of mathematical ability is still in its infancy. And as such, there is a pressing need for neuroscience to continue to investigate the underlying brain structures and circuitry that may serve as the physiological foundation of exceptional math ability. Such findings will undoubtedly assist parents and teachers in ensuring the optimal development of math skills in all children irrespective of their ability level.

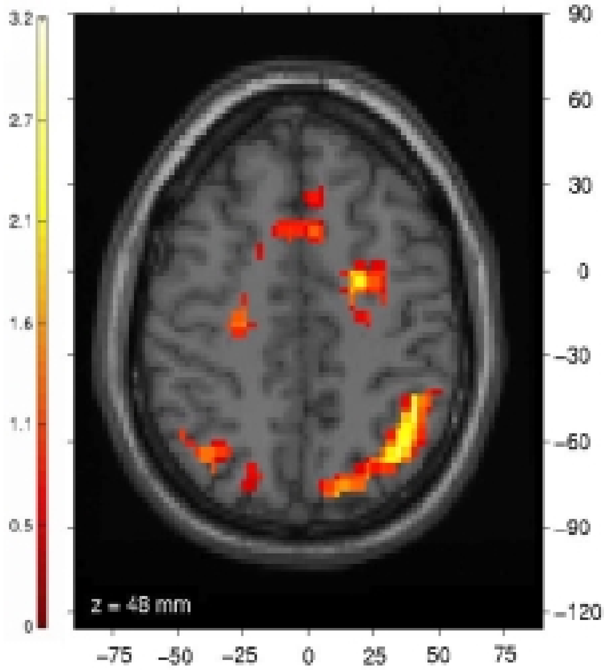

Figure 2. Active regions in mental rotation (T scores)

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